Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 133 (2015) 681 – 687

Procedia Engineering

www.elsevier.com/locate/procedia

6th Fatigue Design conference, Fatigue Design 2015

Crack propagation in Large Scale Yielding (LSY) conditions

Gaëlle Leopold*[a], Rémi Munier[a]

[a]*EDF R&D, Département MMC, Avenue des Renardières Ecuelles BP.46, 77818 Moret-Sur-Loing Cedex*

Abstract

In Industry, some components are subjected to fatigue thermal loadings due to thermal fluctuations coming from the meet of a cold and a hot fluid. A Large Scale Yielding (LSY) conditions zone can be created: plasticity is not only located at the crack tip, but extends to a larger area of the component. Thus, traditional hypothesis of elasticity cannot be used for numerical predictions. Nevertheless, crack propagation needs to be estimated with adapted numerical models.

Thermomechanical fatigue crack propagation tests are performed with an EDF facility in the desired large scale yielding conditions. During the thermal fatigue tests, temperatures, strains and surface crack lengths are measured and registered. Microscopic analyses are carried out in order to observe the influence of the microstructure on the fatigue crack path.

This paper presents first experiments performed with the PACIFIC test rig and first results get for crack propagation in Large Scale Yielding conditions.

Peer-review under responsibility of CETIM

Keywords: Crack propagation ; Large Scale Yielding ; Thermal Fatigue

1. Introduction

Some components of PWR plants can be submitted to cyclic thermal loadings due to thermal fluctuations coming from the meet of a cold and a hot fluid. Those feature loadings may introduce high stress and strain fields. A state of

* Corresponding author. Tel.: +33 1 60 73 74 82; fax: +33 1 60 73 65 59.
E-mail address: gaelle.leopold@edf.fr

1877-7058
Peer-review under responsibility of CETIM
doi:10.1016/j.proeng.2015.12.650

extended plasticity can be induced because of a non zero cyclic plastic strain: this is the definition of the Large Scale Yielding (LSY) conditions studied in this paper. In order to insure safety of components, we need to be able to predict the crack propagation from a hypothetical defect in LSY conditions [1].

Crack propagation is usually designed using Elastic Fracture Mechanics (EFM) tools. But, these tools, as the well known Paris's law [2], cannot be used in LSY conditions. A new crack propagation law needs to be developed for those specific conditions. Some new experimental data are so necessary.

A new test rig, named PACIFIC [3], was developed by R&D Division of EDF to perform crack propagation tests with an extended plasticity state and a cyclic thermomecanical loading.

Nomenclature

EFM	Elastic Fracture Mechanics
LSY	Large Scale Yielding
PWR	Pressurized Water Reactor
SIF	Stress Intensity Factor
da/dN	Crack growth rate
ΔK	Amplitude of the stress intensity factor equal to the maximal value, K_{min}, less the minimal value K_{max}
K_{min}	Minimal value of the stress intensity factor
K_{max}	Minimal value of the stress intensity factor

2. Presentation of the PACIFIC test rig

The PACIFIC test rig was developed to perform fatigue crack propagation tests in LSY conditions (Fig. 1). A cyclic thermomechanical load is applied using four circuits. Four different temperatures can be applied on the mock-up and so different kind of thermal gradients can be created. The maximal temperature that can be reached on these four circuits is 240°C.

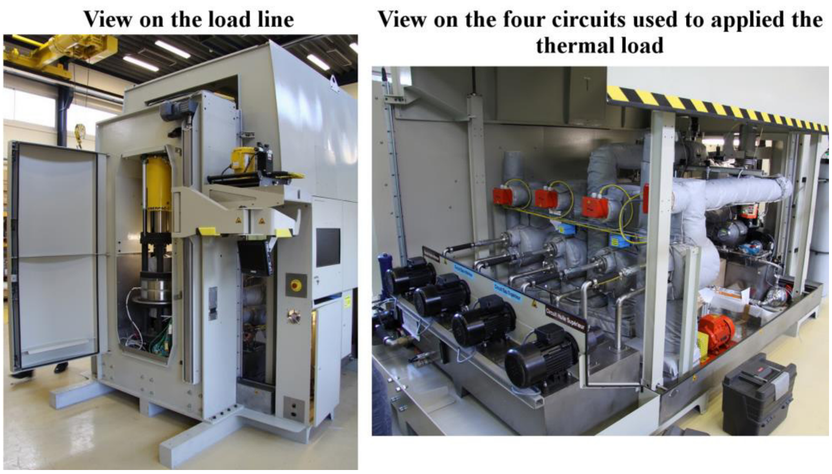


Fig. 1: The PACIFIC test rig

The PACIFIC mock-up is composed of a central disk holed in its center and an external ring welded to it (Fig. 2 (a)). The central part contains the four initial cracks with one or two different surface crack lengths. Thermal loads are applied on the central part using two water injections and on the external ring by conduction with two oil circuits (Fig. 2 (b)). The crack propagation experiment occurs in a water environment.

PACIFIC tests take place under a safety cover because of pressure and temperatures used (Fig. 1). The mock-up is equipped with thermocouples and strain gauges in order to record experimental data useful for analysis and interpretation of the test. Several thermocouples are placed at the surface of the central disk and in the thickness of the external ring. Strain gauges are placed only at the surface of the central disk far from the cracked areas.

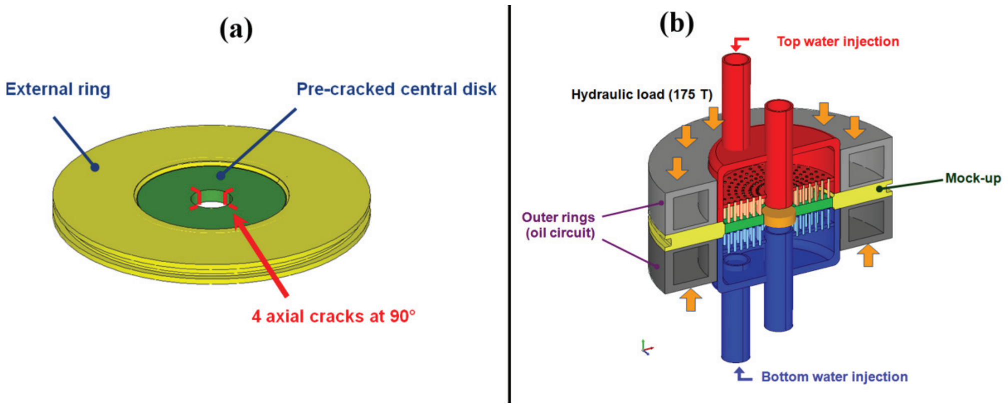


Fig. 2: (a) The PACIFIC mock-up (b)

Using the four circuits, three types of thermal gradients can be created: an axial gradient, a radial gradient or both axial and radial gradients (Fig. 3). For the following presented results, both axial and thermal gradients are generated in the mock-up.

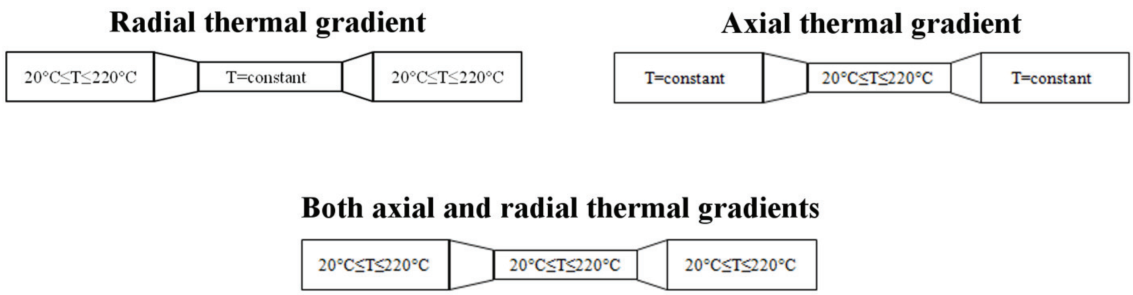


Fig. 3: Types of possible thermal gradients with the PACIFIC facility

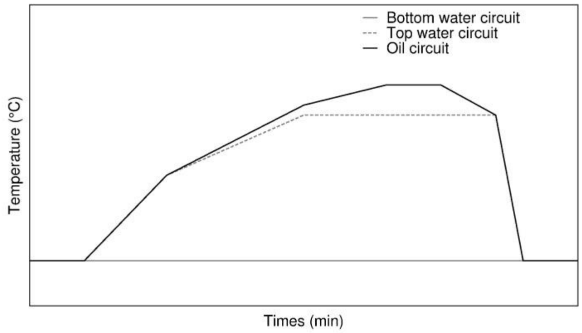
Objectives of PACIFIC experiments are to generate experimental data of LSY type crack propagation. First, these data will be used to have a better understanding of mechanisms which take place during this particular propagation. Then, they will also be used to quantify crack propagation rate for specific thermomechanical conditions. And, these data will be the input data for development and validation of a new crack propagation model able to consider LSY conditions. So, surface crack lengths are measured during the test as well as strains and fracture surfaces are observed.

3. PACIFIC fatigue test characteristics

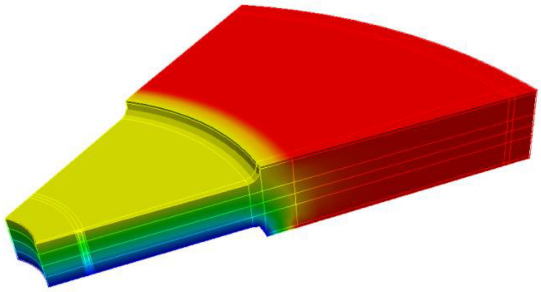
A PACIFIC experiment is characterized by the length of the four initial cracks and the thermal cycle which will be applied on the mock-up. These conditions are determined using a 3D thermomecanical Finite Element calculation in order to be representative of the studied operating transients of PWR French plants. The Stress Intensity Factor (SIF) is the mechanical parameter used to compare computations of the PACIFIC mock-up to real components.

The four circuits are used to induce both an axial and a radial gradient (Fig. 4(a)). This thermal cycle lasts one hour and a half. There is an axial thermal gradient between faces of the central disk (Fig. 4 (b)): the maximal temperature reached for the bottom and the top water circuits are different. There is a radial thermal gradient between the central disk and the external ring (Fig. 4(b)): the maximal temperature reached on the external ring is greater than the maximal temperature reached on the hottest face heated with water.

Initial crack lengths and the applied temperatures are optimized to reach a maximal value of SIF equal to 100 MPa.m$^{1/2}$ which is calculated in linear elastic conditions.



(a)



(b)

Fig. 4: (a) Thermal cycle, (b) EF calculation of distribution of temperatures during the holding time

4. Results

Measurements of temperatures show that cycles are repetitive. Desired temperatures are reached in the central disk of the mock-up during the holding time especially in cracked areas (Fig. 5). The strain measured on the cold face evolves with the temperature: it grows, is constant and decreases with the temperature of the hot face. Far from cracks, the strain amplitude is equal to 0,0015 (Fig. 6).

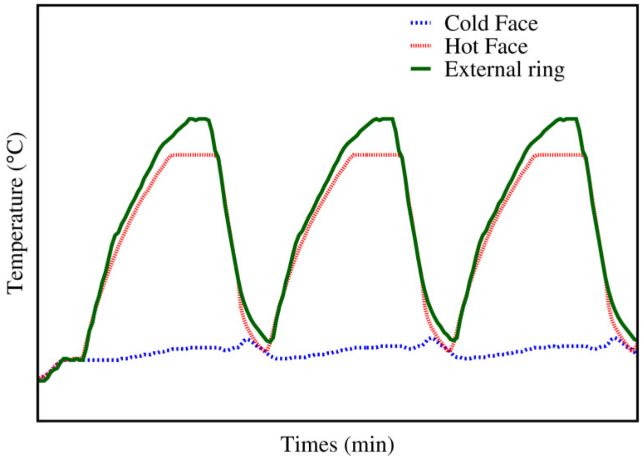


Fig. 5: Temperatures measured on the PACIFIC mock-up

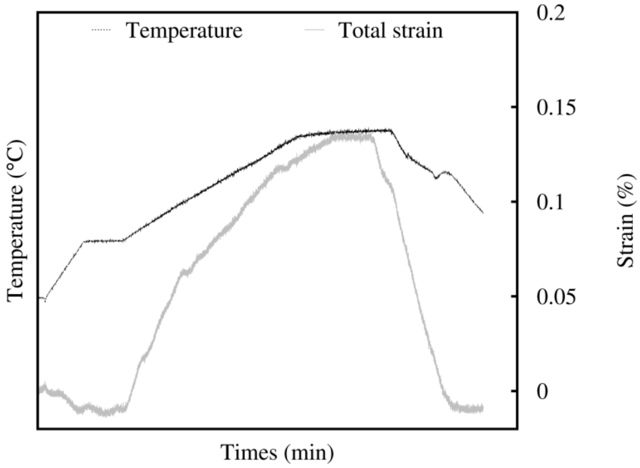


Fig. 6: Strain gauges measurements

The PACIFIC test is periodically interrupted to measure the surface crack lengths with an optical technique and a (X,Y) table. Crack propagation is mainly observed on the coldest face (Fig. 7) whereas any is observed on the hottest face. It can be noticed that the evolution of crack length is linear with the number of cycles.

The four initial cracks propagate in the main direction but their paths can be tortuous. These disturbances seem to be mainly influenced by microstructure (Fig. 8). Fracture surfaces are characterized with the presence of striations. In LSY conditions, cracks propagate through creation of striation (Fig. 9).

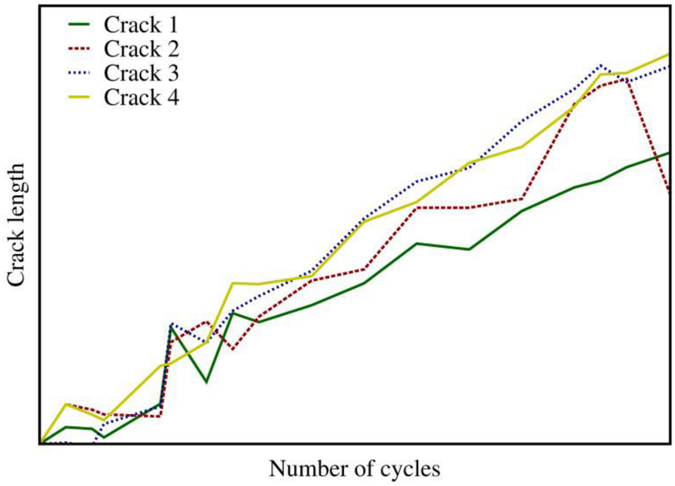


Fig. 7: Evolution of crack lengths measured on the coldest face

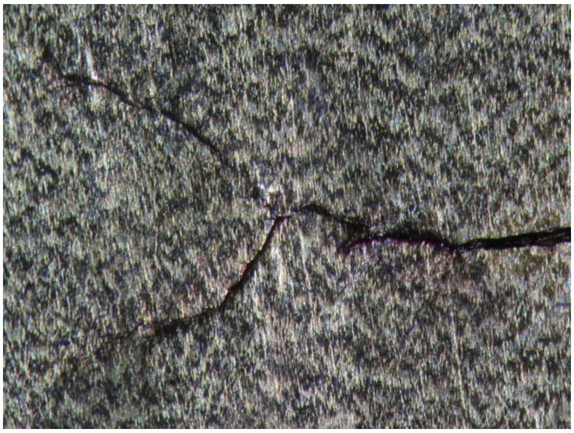


Fig. 8: Photograph of crack n°1

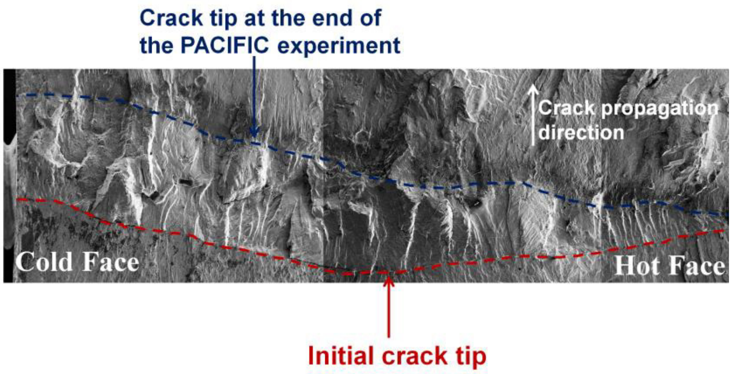


Fig. 9: Fracture surface

The theoretical maximal value of the stress intensity factor, estimated by 3D EF calculations, was used to determine test conditions: initial crack lengths and temperatures. This parameter is now estimated, using equation 1 which is the PWR crack growth law and the experimental measured crack lengths (Fig. 7), to compare computations to the experiment: the maximal SIF is equal to 65 $MPa.m^{1/2}$. This value is lower than the value estimated with the 3D elastic Finite Element calculation. This result shows that in LSY conditions, the crack growth rate is lower than the one calculated with an elastic calculation. The elastic calculation used to design and justify safety of real components is conservative.

$$\frac{da}{dN} = 1{,}8.10^{-9}\left(\frac{\Delta K}{1-\frac{1}{2}\frac{K_{\min}}{K_{\max}}}\right)^{4} \tag{1}$$

5. Conclusions

A test rig, named PACIFIC, was developed by the R&D division of EDF to perfom fatigue crack propagation tests in Large Scale Yielding conditions with a cyclic thermomecanical load applied to an axisymmetric mock-up. This set-up allows studying different combinations of thermal conditions and so studying several mechanical states.

First experiments carried out with this test rig have shown some characteristics of the crack propagation in LSY conditions. These first results have confirmed that justification methods are still conservative according to crack propagation in LSY conditions from an initial crack.

New numerical tools able to take into account these specific conditions of plasticity are necessary and need to be developed to predict crack propagation rate from a hypothetical defect.

References

[1] W. Zhang, S. Pommer, F. Curtit, G. Leopold, S. Courtin, Mode I crack propagation under high cyclic loading in 316L stainless steel, Procedia Mat. Sci. 3 (2014) 1197-1203.

[2] P. C. Paris, A rational analytic theory of fatigue, The trend in engineering (1961) 528-534.

[3] C. Vallet, T. Chau, J. Stephan, Crack propagation under high thermal amplitude cycles in a ductile material, Proceedings of ASME 2012 Pressure Vessels and Piping Conference